# Appendix G
# Global Warming Potentials

## Overview

Global warming potentials (GWPs) are indices used to compare the abilities of different greenhouse gases to trap heat in the atmosphere. GWPs are based on the radiative forcing effects[1] (heat-absorbing ability) of each gas relative to that of carbon dioxide ($CO_2$), as well as the decay rate of each gas (the amount removed from the atmosphere over a given number of years) relative to that of $CO_2$. The GWP for a gas provides a construct for converting emissions of each GHG into a common measure, which allows analysts to aggregate and compare the radiative impacts of various greenhouse gases into a uniform measure denominated in carbon dioxide equivalents ($CO_2e$). Thus, applying the appropriate GWP to a greenhouse gas will yield the $CO_2e$ of the greenhouse gas being measured. GWPs can also serve as an important quantitative tool for governments and policymakers seeking consensus in formulating an effective climate policy.

In preparing the estimations of emissions provided in *Emissions of Greenhouse Gases in the United States*, the Energy Information Administration (EIA) seeks to employ the most current data sources. In doing so, EIA has generally relied on the GWPs published in assessment reports by the Intergovernmental Panel on Climate Change (IPCC) prepared every five years. Over the past decade, the IPCC has conducted an extensive research program aimed at determining the sources and effects of various greenhouse gases and their effect on the climate system. The results of that work were originally released in 1995 in an the IPCC first assessment report, *Climate Change 1994*,[2] and subsequently updated in their second assessment report (SAR) *Climate Change 1995*[3] and third assessment report (TAR) *Climate Change 2001*.[4]

There has been some discussion about which GWPs to utilize in preparing estimates of greenhouse gas emissions, largely stemming from the different stages of publication and formal approval of the IPCC's SAR, published in 1996, and the TAR, published in 2001. The United Nations Framework Convention on Climate Change (UNFCCC) requirements for developing national inventories—provided under the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* and the UNFCCC's *Guidelines on Reporting and Review*[5] for national inventories—were developed prior to the publication of the TAR. Both documents continue to require national inventories to be based on the GWPs in the IPCC SAR,[6] and the UNFCCC negotiating body, called the Conference of Parties (COP), has yet to adopt decisions to approve the TAR.[7] As a result, the U.S. Environmental Protection Agency (EPA) and a number of national governmental bodies responsible for publishing and submitting national emissions inventories to the UNFCCC utilize the GWPs published in the SAR.

In contrast, EIA's *Emissions of Greenhouse Gases* has relied on the high likelihood that the TAR, as published, will be adopted and approved by the COP in the near future, and that there is little reason not to utilize the TAR GWP values but for the fact that the COP has yet to formally adopt the TAR. For this year's *Emissions* report, EIA has added this new appendix to address the differences between the GWPs presented in the SAR and TAR, and to explain the rationale for applying the GWPs from the TAR.

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[1] Radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in Watts per square meter ($W/m^2$).

[2] Intergovernmental Panel on Climate Change, *Climate Change 1994: Radiative Forcing of Climate Change* (Cambridge, UK: Cambridge University Press, 1995).

[3] Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).

[4] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001).

[5] Conference of Parties, Fifth Session, United Nations Framework Convention on Climate Change (UNFCCC) Guidelines on Reporting and Review, FCCC/CP/1999/7 (16 February 2000).

[6] See *Revised Guidelines for the Preparation of National Communications by Parties included in Annex I to the Convention*, FCCC/CP/1996/15/Add.1 (1996).

[7] See decision 2/CP.3 of the UNFCCC.

## Understanding Global Warming Potentials

A global warming potential (GWP) is defined as the cumulative radiative forcing—both in terms of direct effects and indirect effects (such as resulting from chemical transformations)—over a period of time, relative to a reference gas.[8] GWP values are derived from laboratory experiments on molecular attributes of greenhouse gases and data modeling of the gases' radiative transfer properties.[9] While any time period can be selected, the IPCC recommends using 100-year GWPs. According to the IPCC, the direct GWPs for gases with distinguished lifetimes have an estimated uncertainty within ±35%, but the indirect GWPs are less certain, particularly those for which lifetimes are not yet understood.[10] Table G1 illustrates the differences in estimated GWP values as a factor of time horizons.

**Table G1. Numerical Estimates of Global Warming Potentials Compared With Carbon Dioxide**
(Kilogram of Gas per Kilogram of Carbon Dioxide)

| Gas | Lifetime (Years) | Direct Effect for Time Horizons of | | |
|---|---|---|---|---|
| | | 20 Years | 100 Years | 500 Years |
| **Carbon Dioxide** | 5 – 200[a] | 1 | 1 | 1 |
| **Methane** | 12 | 62 | 23 | 7 |
| **Nitrous Oxide** | 114 | 275 | 296 | 156 |
| **Hydrofluorocarbons, Perfluorocarbons, and Sulfur Hexafluoride** | | | | |
| HFC-23 | 260 | 9,400 | 12,000 | 10,000 |
| HFC-125 | 29 | 5,900 | 3,400 | 1,100 |
| HFC-134a | 13.8 | 3,300 | 1,300 | 400 |
| HFC-152a | 1.4 | 410 | 120 | 37 |
| HFC-227ea | 33 | 5,600 | 3,500 | 1,100 |
| Perfluoromethane ($CF_4$) | 50,000 | 3,900 | 5,700 | 8,900 |
| Perfluoroethane ($C_2F_6$) | 10,000 | 8,000 | 11,900 | 18,000 |
| Sulfur Hexafluoride ($SF_6$) | 3,200 | 15,100 | 22,200 | 32,400 |

[a] No single lifetime can be defined for carbon dioxide due to different rates of uptake by different removal processes.
Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), pp. 38 and 388-389.

Greenhouse gases with relatively long atmospheric lifetimes (e.g., carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. Short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, and other ambient air pollutants (e.g., nitrogen oxide, and non methane volatile organic compounds), and tropospheric aerosols (e.g., sulfur dioxide products and black carbon), however, are present in very different quantities spatially around the world, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these gases that are short-lived and spatially heterogeneous in the atmosphere.[11]

## Changes between the Second and Third Assessment Reports

More than two decades of research have provided a progressively improved understanding of the interaction between anthropogenic emissions of greenhouse gases and their potential to alter the Earth's atmosphere. In the five years between the publication of the SAR in 1996 and the TAR in 2001, considerable progress was achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences.

The IPCC's TAR includes GWP estimates for several gases that have been modified from the SAR, as well as new GWPs for a more complete set of gases. In keeping with IPCC protocol, the use of all GWPs continues to be based

[8] U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002. See also Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996).
[9] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6.12.
[10] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2001) Section 6, Executive Summary.
[11] U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002.

on the effect of that greenhouse gas over a 100-year time period. Included among the new gases are certain ozone depleting substances (ODSs), originally considered only to be harmful to stratospheric ozone but now recognized as potent greenhouse gases. In addition, the TAR includes new categories for ethers and halogenated ethers.

In general, the TAR served to confirm and reinforce the conclusions put forth in the SAR. Table G2 provides a comparison of 100-year GWP estimates from the SAR and TAR. The bulk of changes to the GWPs, as described below, have also shown to have little overall impact on the quantification of total greenhouse gases emitted at the U.S. national level. Table G3 presents a comparison of GWPs and lifetimes in the SAR and TAR, while Table G4 illustrates the effect SAR and TAR 100-year GWPs have on U.S. emissions estimates.

**Table G2. Comparison of 100-Year GWP Estimates from the IPCC's Second (SAR) and Third (TAR) Assessment Reports**

| Gas | GWP | | Absolute Change | Percentage Change |
|---|---|---|---|---|
| | SAR | TAR | | |
| **Carbon Dioxide** | 1 | 1 | No Change | No Change |
| **Methane** | 21 | 23 | 2 | 10% |
| **Nitrous Oxide** | 310 | 296 | -14 | -5% |
| **Hydrofluorocarbons** | | | | |
| HFC-23 | 11,700 | 12,000 | 300 | 3% |
| HFC-32 | 650 | 550 | -100 | -15% |
| HFC-41 | 150 | 97 | -53 | -35% |
| HFC-125 | 2,800 | 3,400 | 600 | 21% |
| HFC-134 | 1,100 | 1,100 | 100 | 10% |
| HFC-134a | 1,300 | 1,300 | No Change | No Change |
| HFC-143 | 300 | 330 | 30 | 10% |
| HFC-143a | 3,800 | 4,300 | 500 | 13% |
| HFC-152 | NA | 43 | NA | NA |
| HFC-152a | 140 | 120 | -20 | -14% |
| HFC-161 | NA | 12 | NA | NA |
| HFC-227ea | 2,900 | 3,500 | 600 | 21% |
| HFC-236cb | NA | 1,300 | NA | NA |
| HFC-236ea | NA | 1,200 | NA | NA |
| HFC-236fa | 6,300 | 9,400 | 3,100 | 49% |
| HFC-245ca | 560 | 640 | 80 | 14% |
| HFC-245fa | NA | 950 | NA | NA |
| HFC-365mfc | NA | 950 | NA | NA |
| HFC-4310mee | 1,300 | 1,500 | 200 | 15% |
| **Iodocarbons** | | | | |
| FIC-1311 | <1 | 1 | No Change | No Change |
| **Fully Fluorinated Species** | | | | |
| $SF_6$ | 23,900 | 22,000 | -1,900 | -8% |
| $CF_4$ | 6,500 | 5,700 | -800 | -12% |
| $C_2F_6$ | 9,200 | 11,900 | 2,700 | 29% |
| $C_3F_8$ | 7,000 | 8,600 | 1,600 | 23% |
| $C_4F_{10}$ | 7,000 | 8,600 | 1,600 | 23% |
| c-$C_4F_8$ | 8,700 | 10,000 | 1,300 | 15% |
| $C_5F_{12}$ | 7,500 | 8,900 | 1,400 | 19% |
| $C_6F_{14}$ | 7,400 | 9,000 | 1,600 | 22% |

Sources: Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

## Improvements to GWP Estimates in the Third Assessment Report

Improvements to the IPCC's GWP values in the TAR were a result of an improved calculation of $CO_2$ radiative forcing, an improved $CO_2$ response function, and recalculations of some atmospheric lifetimes. GWPs presented in the TAR are drawn from the SAR and the World Meteorological Organization (WMO),[12] and include specific updates drawn from new published cases of laboratory or radiative transfer results.

[12]World Meteorological Organization, *Scientific Assessment of Ozone Depletion, Global Ozone Research and Monitoring Project-Report No. 44,* Geneva, Switzerland (1999).

As stated in the TAR:

> *The direct GWPs have been calculated relative to $CO_2$ using an improved calculation of the $CO_2$ radiative forcing, the SAR response function for a $CO_2$ pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.* [TAR 2001]

To determine the direct radiative forcings (per ppbv or parts per billion volume), the IPCC "derived from infrared radiative transfer models based on laboratory measurements of the molecular properties of each substance and considering the molecular weights."[13] The radiative forcing of $CO_2$ was found to be about 12 percent lower than that reported in the SAR. For example, the improved formula, for fixed changes in gas concentrations, decreased $CO_2$ and $N_2O$ radiative forcing by 15%, increased CFC-11 and CFC-12 radiative forcing by 10 to 15%, and yielded no change in the case of $CH_4$. As a consequence of changes in the radiative forcing for $CO_2$ and CFC-11, the revised GWPs are typically 20% higher than listed in the SAR.[14]

The response function for a $CO_2$ pulse can be explained in simple terms as the response from adding an additional ton of $CO_2$ to the atmosphere, and the function specifies the proportion of $CO_2$ that remains in the atmosphere after a designated amount of time (an average of single exponential decay functions). The GWP of any substance therefore expresses the integrated forcing of a pulse (of given small mass) of that substance relative to the integrated forcing of a pulse (of the same mass) of the reference gas over some time horizon.

Many atmospheric lifetimes were recalculated in the TAR. The lifetimes of non-$CO_2$ greenhouse gases are dependent largely on atmospheric photochemistry, which controls photo-lysis and related removal processes. When the lifetime of the gas in question differs substantially from the response time of the reference gas ($CO_2$), the GWP becomes sensitive to the choice of time horizon. For example, for longer time horizons (greater than 100 years), those gases that decay more rapidly than the $CO_2$ display decreasing GWPs; and conversely those gases with lifetimes much longer than that of the $CO_2$ display increasing GWPs. Table G3 provides a comparison of the lifetimes and GWPs for the greenhouse gases provided in the SAR and TAR, showing a range of between -15 and + 49 percent in GWP values.

As a result of the adjustments to the radiative forcing of $CO_2$ and the recalculation of atmospheric lifelines of several gases, the GWPs of the other gases, relative to $CO_2$, have overall increased. Other variables, such as the radiative efficiency or chemical lifetime, have also altered the GWP values.[15] Because much detailed laboratory data are not yet available, however, some of the GWPs have larger uncertainties than others. As mentioned above, the IPCC estimates that GWPs generally have an uncertainty of ±35 percent.

Because GWP values are based on the concept of radiative forcing, and these forcings do not appear to stay constant over time, the values for GWPs also will continue to fluctuate, particularly if the amounts and composition of the various gases in the atmosphere increase. In some cases, where concentrations of a greenhouse gas are low, small emissions of the gas will have a disproportionate absorptive effect. However, if concentrations of the gas rise over time, the marginal effects of additional emissions may not be as large. Therefore, the effect of an additional unit of emission of a gas that is relatively plentiful in the atmosphere, such as water vapor or $CO_2$, tends to be less than that of a rare gas, such as sulfur hexafluoride ($SF_6$). This "diminishing return" effect implies that increasing concentrations of a particular gas reduces the impact of additional quantities of that gas. Thus, the relative impacts of various gases will change as their relative concentrations in the atmosphere change.

Figure G1 shows the comparative global and annual mean radiative forcing of a range of gases from 1750 to the late 1990s. Note that greenhouse gases are provided in the left-most bar in the graphic. The IPCC notes that, all the forcings shown have distinct spatial and seasonal features such that the global, annual means appearing on this plot do not yield a complete picture of the radiative perturbation. They are only intended to give, in a relative sense, a first-order perspective on a global, annual mean scale, and cannot be readily employed to obtain the climate response to the total natural and/or anthropogenic forcings. As in the SAR, it is emphasized that the positive and negative global mean forcings cannot be added up and viewed a priori as providing offsets in terms of the complete global climate impact.

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[13] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000), Section 6.12.1.

[14] Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

[15] U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*, April 2002.

## Table G3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR

| Gas | Lifetime (years) | | GWP (100 year) | | Absolute Change | Percent Change |
|---|---|---|---|---|---|---|
| | SAR | TAR | SAR | TAR | | |
| **Carbon Dioxide** | 50-200 | 5-200[a] | 1 | 1 | NC | NC |
| **Methane**[b] | 12±3 | 8.4/12[c] | 21 | 23 | 2 | 10% |
| **Nitrous Oxide** | 120 | 120/114 [c] | 310 | 296 | (14) | -5% |
| **Hydrofluorocarbons** | | | | | | |
| HFC-23 | 264 | 260 | 11,700 | 12,000 | 300 | 3% |
| HFC-32 | 5.6 | 5.0 | 650 | 550 | (100) | -15% |
| HFC-41 | 3.7 | 2.6 | 150 | 97 | (53) | -35% |
| HFC-125 | 32.6 | 29 | 2,800 | 3,400 | 600 | 21% |
| HFC-134 | 10.6 | 9.6 | 1,000 | 1,100 | 100 | 10% |
| HFC-134a | 14.6 | 13.8 | 1,300 | 1,300 | NC | NC |
| HFC-143 | 3.8 | 3.4 | 300 | 330 | 30 | 10% |
| HFC-143a | 48.3 | 52 | 3,800 | 4,300 | 500 | 13% |
| HFC-152 | NA | 0.5 | NA | 43 | NA | NA |
| HFC-152a | 1.5 | 1.4 | 140 | 120 | (20) | -14% |
| HFC-161 | NA | 0.3 | NA | 12 | NA | NA |
| HFC-227ea | 36.5 | 33.0 | 2,900 | 3,500 | 600 | 21% |
| HFC-236cb | NA | 13.2 | NA | 1,300 | NA | NA |
| HFC-236ea | NA | 10 | NA | 1,200 | NA | NA |
| HFC-236fa | 209 | 220 | 6,300 | 9,400 | 3,100 | 49% |
| HFC-245ca | 6.6 | 5.9 | 560 | 640 | 80 | 14% |
| HFC-245fa | NA | 7.2 | NA | 950 | NA | NA |
| HFC-365mfc | NA | 9.9 | NA | 890 | NA | NA |
| HFC-4310mee | 17.1 | 15 | 1,300 | 1,500 | 200 | 15% |
| **Iodocarbons** | | | | | | |
| FIC-1311 | <0.005 | 0.005 | <1 | 1 | NC | NC |
| **Fully Fluorinated Species** | | | | | | |
| $SF_6$ | 3,200 | 3,200 | 23,900 | 22,000 | (1,900) | -8% |
| $CF_4$ | 50,000 | 50,000 | 6,500 | 5,700 | (800) | -12% |
| $C_2F_6$ | 10,000 | 10,000 | 9,200 | 11,900 | 2,700 | 29% |
| $C_3F_8$ | 2,600 | 2,600 | 7,000 | 8,600 | 1,600 | 23% |
| $C_4F_{10}$ | 2,600 | 2,600 | 7,000 | 8,600 | 1,600 | 23% |
| c-$C_4F_8$ | 3,200 | 3,200 | 8,700 | 10,000 | 1,300 | 15% |
| $C_5F_{12}$ | 4,100 | 4,100 | 7,500 | 8,900 | 1,400 | 19% |
| $C_6F_{14}$ | 3,200 | 3,200 | 7,400 | 9,000 | 1,600 | 22% |
| **Ethers & Halogenated Ethers** | | | | | | |
| CH3OCH3 | NA | 0.015 | NA | 1 | NA | NA |
| (CF3)2CFOCH3 | NA | 3.4 | NA | 330 | NA | NA |
| (CF3)CH2OH | NA | 0.5 | NA | 57 | NA | NA |
| CF3CF2CH2OH | NA | 0.4 | NA | 40 | NA | NA |
| (CF3)2CHOH | NA | 1.8 | NA | 190 | NA | NA |
| HFE-125 | NA | 150 | NA | 14,900 | NA | NA |
| HFE-134 | NA | 26.2 | NA | 6,100 | NA | NA |
| HFE-143a | NA | 4.4 | NA | 750 | NA | NA |
| HCFE-235da2 | NA | 2.6 | NA | 340 | NA | NA |
| HFE-245cb2 | NA | 4.3 | NA | 580 | NA | NA |
| HFE-245fa2 | NA | 4.4 | NA | 570 | NA | NA |
| HFE-254cb2 | NA | 0.22 | NA | 30 | NA | NA |
| HFE-347mcc3 | NA | 4.5 | NA | 480 | NA | NA |
| HFE-356pcf3 | NA | 3.2 | NA | 430 | NA | NA |
| HFE-374pcf2 | NA | 5.0 | NA | 540 | NA | NA |
| HFE-7100 | NA | 5.0 | NA | 390 | NA | NA |
| HFE-7200 | NA | 0.77 | NA | 55 | NA | NA |
| H-Galden 1040x | NA | 6.3 | NA | 1,800 | NA | NA |
| HG-10 | NA | 12.1 | NA | 2,700 | NA | NA |
| HG-01 | NA | 6.2 | NA | 1,500 | NA | NA |

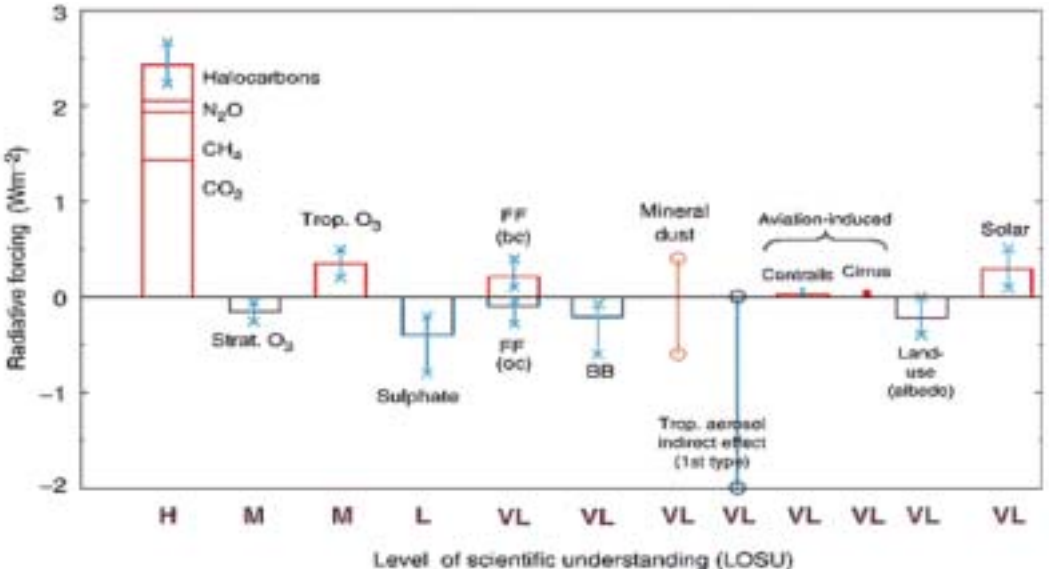
See notes at end of table.

## Table G3. Comparison of GWPs and Lifetimes Used in the SAR and the TAR (Continued)

| Gas | Lifetime (years) | | GWP (100 year) | | Absolute Change | Percent Change |
|---|---|---|---|---|---|---|
| | SAR | TAR | SAR | TAR | | |
| **Others**[d] | | | | | | |
| NF3 | NA | 740 | NA | 10,800 | NA | NA |
| SF5CF3 | NA | >1,000 | NA | >17,500 | NA | NA |
| c-C3F6 | NA | >1,000 | NA | >16,800 | NA | NA |
| HFE-227ea | NA | 11 | NA | 1,500 | NA | NA |
| HFE-236ea2 | NA | 5.8 | NA | 960 | NA | NA |
| HFE-236fa | NA | 3.7 | NA | 470 | NA | NA |
| HFE-245fa1 | NA | 2.2 | NA | 280 | NA | NA |
| HFE-263fb2 | NA | 0.1 | NA | 11 | NA | NA |
| HFE-329mcc2 | NA | 6.8 | NA | 890 | NA | NA |
| HFE-338mcf2 | NA | 4.3 | NA | 540 | NA | NA |
| HFE-347-mcf2 | NA | 2.8 | NA | 360 | NA | NA |
| HFE-356mec3 | NA | 0.94 | NA | 98 | NA | NA |
| HFE-356pcc3 | NA | 0.93 | NA | 110 | NA | NA |
| HFE-356pcf2 | NA | 2.0 | NA | 260 | NA | NA |
| HFE-365mcf3 | NA | 0.11 | NA | 11 | NA | NA |
| (CF3)2CHOCHF2 | NA | 3.1 | NA | 370 | NA | NA |
| (CF3)2CHOCH3 | NA | 0.25 | NA | 26 | NA | NA |
| (CF2)4CH(OH)- | NA | 0.85 | NA | 70 | NA | NA |

[a] No single lifetime can be determined for carbon dioxide. (See IPCC 2001)
[b] The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of $CO_2$ is not included.
[c] Methane and nitrous oxide have chemical feedback systems that can alter the length of the atmospheric response, in these cases, global mean atmospheric lifetime (LT) is given first, followed by perturbation time (PT).
[d] Gases whose lifetime has been determined only via indirect means of for whom there is uncertainty over the loss process.
Sources: U.S. Environmental Protection Agency (EPA), *Greenhouse Gases And Global Warming Potential Values: Excerpt from the inventory of u.s. Greenhouse Emissions and Sinks: 1990-2000,* April 2002; Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).
Notes: NC (No Change); NA (Not Applicable)

## Figure G1. Global and Annual Mean Radiative Forcing (1750 to Present)




Notes: This figure illustrates the global, annual mean radiative forcings ($Wm^{-2}$) due to a number of agents for the period from pre-industrial (1750) to the late 1990s (about 2000). The height of the rectangular bar denotes a central or best estimate value while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with "x" delimiters indicates an estimate of the uncertainty range, guided by the spread in the published values of the forcing and physical understanding. A vertical line without a rectangular bar and with "o" delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. The uncertainty range specified here has no statistical basis and therefore differs from the use of the term elsewhere in this document. A "level of scientific understanding" (LOSU) index is accorded to each forcing, with H, M, L and VL denoting high, medium, low and very low levels, respectively. This represents our subjective judgment about the reliability of the forcing estimate, involving factors such as the assumptions necessary to evaluate the forcing, the degree of our knowledge of the physical/chemical mechanisms determining the forcing, and the uncertainties surrounding the quantitative estimate of the forcing. The well-mixed greenhouse gases are grouped together into a single rectangular bar with the individual mean contributions due to $CO_2$, $CH_4$, $N_2O$, and halocarbons shown; halocarbons refers to all halogen-containing compounds listed in "FF" denotes fossil fuel burning while "BB" denotes biomass burning aerosol. Fossil fuel burning is separated into the "black carbon" (bc) and "organic carbon" (oc) components with its separate best estimate and range. The sign of the effects due to mineral dust is itself an uncertainty. Only the first type of indirect effect due to aerosols as applicable in the context of liquid clouds is considered here.
Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

## Effect of Using TAR GWPs for Greenhouse Gas Emissions Estimations

As shown in Table G4, when estimating U.S. greenhouse gas emissions for 1990, 2000 and 2001, the values calculated with the TAR GWPs are 0.7 to 0.8 percent higher than the estimate calculated with SAR GWPs. When applying the TAR GWPs, the greatest overall difference to the SAR estimates, in terms of having a significant effect on the atmosphere, can be seen in a 10.0 percent increase in carbon-equivalent methane emissions and a 4.0 percent decrease in carbon-equivalent nitrous oxide emissions. Carbon equivalent emissions of HFCs, PFCs, and $SF_6$ have varied over the years depending on the relative share of the gases. Taken as a whole, however, the differences in GWPs between the SAR and TAR do not prove a significant effect on U.S. emissions trends.

**Table G4. GWP Effects on U.S. Greenhouse Gas Emissions**

| Gas | IPCC GWP | | Annual GWP-Weighted Emissions (Million Metric Tons Carbon Equivalent) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1990 | | | 2000 | | | 2001 | | |
| | 1996 | 2001 | 1996 GWP | 2001 GWP | Percent Change | 1996 GWP | 2001 GWP | Percent Change | 1996 GWP | 2001 GWP | Percent Change |
| Carbon dioxide | 1 | 1 | 1,364 | 1,364 | 0.0% | 1,597 | 1,597 | 0.0% | 1,579 | 1,569 | 0.0% |
| Methane | 21 | 23 | 181 | 199 | 9.5% | 162 | 178 | 9.5% | 160 | 176 | 10.0% |
| Nitrous oxide | 310 | 296 | 99 | 94 | -4.5% | 103 | 98 | -4.5% | 102 | 97 | -4.0% |
| HFCs, PFCs, and $SF_6$ | — | — | 26 | 25 | -3.8% | 31 | 34 | 9.7% | 28 | 31 | 10.7% |
| **Total** | **—** | **—** | **1,670** | **1,682** | **0.7%** | **1,891** | **1,907** | **0.8%** | **1,868** | **1,883** | **0.8%** |

Sources: U.S. Energy Information Administration, *Emissions of Greenhouse Gases in the United States 2001* (December 2002); Intergovernmental Panel on Climate Change, *Climate Change 1995: The Science of Climate Change* (Cambridge, UK: Cambridge University Press, 1996); and Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (Cambridge, UK: Cambridge University Press, 2000).

# Conclusions

In the five years between the publication of the SAR in 1996 and the TAR in 2001, progress has been achieved in reducing the scientific uncertainty associated with the direct and indirect relationship of atmospheric responses to various external influences. Improvements have been made to the GWP values published in the TAR, and these are expected to be adopted and approved by the UNFCCC COP. While participating countries are still required to apply the GWPs published in the SAR according to the most recently adopted requirements for the development of national GHG inventories submitted to the UNFCCC, the TAR has been recognized as providing the most scientifically accurate GWPs to date, and has been adopted by EIA in the completion of this report.